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Enhancing Fuel Pellet Performance from Agricultural Biomass: Effects of LLDPE Additive, Die Temperature, and Diameter on Properties

Mohammad Hossein Kianmehr[1]✉, Ali Mashaallah Kermani[1], Hossein Beheshti Asl[1], Saba Nasiri[2]

[1]Department of Agricultural Engineering, Aburaihan Campus, University of Tehran, Tehran, Iran
[2]Department of Business Administration, University of Europe for Applied Sciences, Berlin, Germany
✉ Corresponding author: kianmehr@ut.ac.ir

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ABSTRACT

Among the various forms of biomass, agricultural residues represent a promising feedstock for biofuel production, particularly in the form of fuel pellets. These pellets have the potential to mitigate the global fuel shortage; however, they often exhibit suboptimal physical and mechanical properties. In this study, we explore the feasibility of utilizing low-density linear polyethylene (LLDPE) waste as a binder to enhance the quality of fuel pellets produced from agricultural residues. Fuel pellets were manufactured using a single-pellet press from shredded straw and dried grass, with varying proportions of plastic additive. The experimental design incorporated two die diameters (8 mm and 10 mm), three die temperatures (80°C, 120°C, and 160°C), and three levels of LLDPE additive (0%, 15%, and 25% by weight). Each combination was tested in triplicate using a completely randomized factorial design. Key performance indicators such as density, toughness, water retention capacity, moisture content, volatile matter, ash content, fixed carbon percentage, and heating value were assessed. Microstructural analysis of pellet composition was conducted using Scanning Electron Microscopy (SEM) to further understand the impact of the LLDPE additive on pellet morphology. The heating value of the pellets ranged from average of 15.86 MJ/kg to 22.32 MJ/kg, and there was a positive correlation between density and temperature. Pellet density varied between average of 510 kg/m³ and 903 kg/m³, indicating substantial improvements with the inclusion of the LLDPE additive.

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INTRODUCTION

Agriculture is a fundamental industry in every country which results in the generation of vast quantities of agricultural waste annually, necessitating appropriate disposal methods (Duque-Acevedo et al., 2020). Compounding these challenges is the significant rise in global energy demand since the 20th century (Shoaei et al., 2023), which has sparked widespread concerns over potential energy shortages. Moreover, the detrimental environmental impacts of fossil fuels have underscored the urgent need to transition to renewable energy sources (Pang et al., 2019). Among these, biomass represents a particularly promising renewable energy source, as it is derived from biological materials. Biofuels produced from biomass, including forest residues and agricultural products, have the potential to provide up to 70 billion tons of crude oil equivalent energy annually ten times the world's current energy consumption. Agricultural waste, a significant component of biomass, has been recognized as a valuable energy source due to its high proportion of combustible materials suitable for thermal energy production (Acaravci & Erdogan, 2018; Kaltschmitt et al., 2007). Several methods are available for converting biomass into energy, with fuel pellet production emerging as one of the most efficient and widely used approaches (Stelte et al., 2011). Biomass densification techniques, such as pelleting, briquetting, extrusion, and rolling, enhance the energy content and usability of biomass for fuel production (Stelte et al., 2012). Among these, pelletization stands out as a process that produces uniform biofuels characterized by low moisture content and high density, thereby improving the efficiency of biomass as an energy source (Li et al., 2012).

The final quality of biomass pellets is influenced by multiple factors, including the properties and composition of the raw materials, the type and concentration of additives, and the specific process variables employed during production (Arshadi et al., 2008; Gilbert et al., 2009; Kim et al., 2015). Among these, production temperature plays a critical role in determining pellet quality. As the die temperature increases during pelletization, it softens and activates the inherent or added binding agents, which in turn directly affects pellet cohesion and durability (Said et al., 2015). The relationship between temperature and increased pellet density is governed by several mechanisms, including the formation of chemical covalent bonds between adjacent particles, the activation of attractive forces such as hydrogen bonds and van der Waals interactions, and the creation of mechanical bonds between fibers and particles. Additionally, as the elastic modulus of the particles decreases at higher temperatures, the biomass becomes more flexible and easier to compact (Lisowski et al., 2019). Higher temperatures also reduce the distance between particles, leading to denser pellets (Mostafa et al., 2019). For example, in a study on the pelletization of olive tree pruning residues, temperatures above 40°C were found to produce optimal pellet quality (Garcia-Maraver et al., 2015). Similarly, Nasiri and colleagues demonstrated that a temperature of 110°C, combined with a residence time of 5 seconds, provided the best conditions for producing fuel pellets from municipal waste (Nasiri, Hajinezhad, & Kianmehr, 2023). In subsequent research, Nasiri et al. (Nasiri, Hajinezhad, Kianmehr, et al., 2023) explored the combined effects of temperature, retention time, and additives on refuse-derived fuel (RDF) pellet quality, finding that higher temperatures and longer retention times enhanced both pellet strength and calorific value. Another key factor influencing pellet quality is the die size, which affects both the energy required for compression and the physical properties of the resulting pellets. Pellets produced using a smaller die diameter tend to exhibit higher density and reduced moisture content, while larger die diameters often result in lower pellet durability(Oduntan & Koya, 2015). Tumuluru (2018) (Tumuluru, 2018) investigated the impact of die diameter on biomass pellet density and durability, reporting that increasing the die size from 8 mm to 10 mm generally improved pellet density, especially for woody biomass such as lodgepole pine. However, the effect of die size on pellet durability varied depending on the material; for instance, durability increased for lodgepole pine and corn stover but slightly decreased for other biomass types. This underscores the importance of optimizing die diameter to balance pellet density and durability for various energy applications. In addition to die size and temperature, the selection of additives also plays a crucial role in pellet production. Wei et al. (2024) (Wei et al., 2024) highlighted the effectiveness of low-density polyethylene (LDPE), which comprises 17% of global plastic use, as an optimal binder for fuel pellet production. The addition of additives enables the pellet formation process to occur at lower temperatures and with less energy (Cui et al., 2019). In 2019, Liu and colleagues investigated the mechanism of improving the performance of green pellets by adding mixed plastic waste and binders (Liu et al., 2019). In a 2017 study, Emadi and his team examined the effect of polymer plastic additives on the physical, combustion, and storage properties of pellets made from plant biomass. They used linear low-density polyethylene (LLDPE), a plastic extractable from municipal solid waste (MSW), as an additive in biomass pellets. The results showed that adding 6% LLDPE to biomass pellets resulted in a maximum density increase of 1.8% for wheat and 1.7% for barley. Additionally, the inclusion of 10% LLDPE in biomass pellets led to a 280% and 253% increase in tensile strength for wheat and barley, respectively (Emadi et al., 2017).

In Iran, technical expertise for pellet production using die roll machines is well established; however, this capability has been predominantly applied to feed pellets, while the energy potential of abundant lignocellulosic agricultural residues particularly straw and dried grass remains largely untapped. Despite the extensive volume of these residues within the national waste stream, systematic and application-oriented research on their conversion into high-quality fuel pellets is still limited. Furthermore, although numerous studies have examined biomass pelletization, there is a clear lack of comprehensive investigations into the use of polyethylene-based additives, especially waste-derived linear low-density polyethylene (LLDPE), in lignocellulosic fuel pellets. This gap is particularly significant given that LLDPE constitutes a major fraction of municipal plastic waste and offers distinct advantages, including improved binding behavior, enhanced water resistance, and increased calorific value. In addition, the combined and interactive effects of key processing parameters such as die diameter, production temperature, and additive concentration on pellet quality have not been sufficiently addressed in the existing literature. Therefore, the present study addresses these critical gaps by employing a laboratory-scale single-pellet press to systematically evaluate the feasibility of producing high-quality fuel pellets from straw and dried grass residues, with and without LLDPE addition. By elucidating the coupled effects of process variables on pellet density, mechanical performance, water resistance, and energy content, this work provides important insights for the sustainable co-valorization of agricultural and plastic wastes and contributes to advancing practical biofuel pellet technologies.

MATERIALS AND METHODS

In this study, dried wheat straw and grass clippings from lawn trimming, both agricultural residues, were used to produce fuel pellets and to determine their physical properties. Additionally, polyethylene plastic, a type of synthetic material, was used as an additive. The effects of various production process parameters on the quality characteristics of the produced fuel pellets were examined.

Sample Preparation

For the production of fuel pellets, raw materials such as plastic, which is one of the most significant types of municipal solid waste, as well as dried wheat straw (autumn wheat, Shiraz variety) and dried grass, which are major agricultural residues, were prepared in accordance with sanitary and laboratory protocols. After collecting the straw and grass, they were spread under direct sunlight for 2 to 3 days to sufficiently reduce their moisture content, making them suitable for grinding. Based on the evaluations, particle sizes between 1 to 3 mm were selected, and the materials were passed through a sieve of the specified mesh size to achieve this.

Pelletization Process

In this study, pellets were produced at three different temperatures: 80, 120, and 160°C, using two die diameters (8 and 10 mm), and with a constant mixture of wheat straw and dried grass, along with three levels of additive (0%, 15%, and 25% by weight). The retention time was set to 5 seconds. The ranges for these parameters (the temperature and time ranges) for the pelletization experiments were selected based on two main considerations: insights from existing studies using comparable raw materials and pelletizing equipment, which provided approximate time and pressure parameters for pellet formation (Nasiri, Hajinezhad, Kianmehr, et al., 2023); and preliminary testing using a trial-and-error approach (Terraria trials), where various temperature and time settings were evaluated (Moliner et al., 2020). The optimal conditions were chosen based on visual inspection, eliminating excessively high temperatures and times that resulted in burning or melting of the pellets, as well as low temperatures and times that led to poor pellet cohesion or disintegr. The press pressure was set to 25 bar. A single-pellet press machine, as shown in Figure 2, was used to produce the pellets (Warajanont & Soponpongpipat, 2013). The pelletizer consists of a piston and cylinder, thermocouple, heating belt, press machine, and temperature controller (Figure 1). To produce the pellets, a pellet die with a closed end was used. The die was made from a cylinder with a height of 10 cm and an internal diameter of either 8 or 10 mm. A piston was used to apply pressure to the materials inside the cylinder (Figure 2).

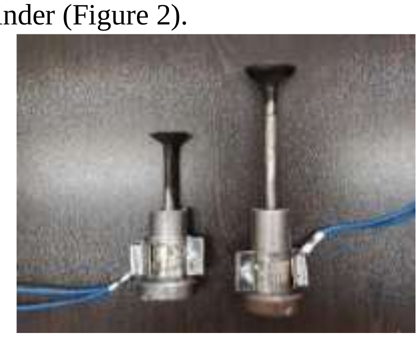

Figure 1. Pellet Die

Figure 2. Press machine with pellet die: 1) Die and position, 2) Pressure gauge and flow control valve, 3) Thermocouple and controller

A ring-shaped heating element equipped with a thermocouple and a thermostat was used to heat the pellet die. For this purpose, a specific mode and temperature (with tolerance) were applied. A two-dimensional cross-sectional diagram of the die and the attached component is shown in Figure 3.

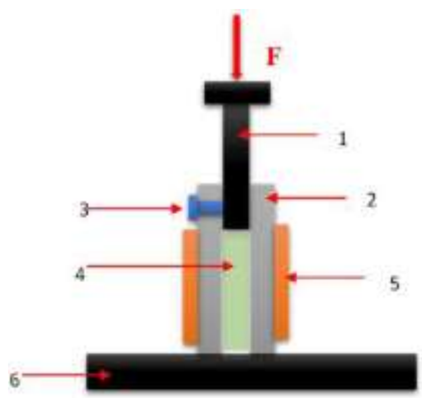

Figure 3. Two-dimensional diagram of the laboratory pellet die (die and heating element): 1) Piston, 2) Cylinder wall (die), 3) Thermocouple, 4) Material mass, 5) Heating element (belt), and 6) Die base for blocking the cylinder

Pellet Characteristics

Pellet density

To determine the actual density, the length, diameter, and mass of each pellet were measured, and the density was calculated according to the standard method (Poddar et al., 2014).

Pellet water resistance time

Water resistance was evaluated by measuring the time required for pellet disintegration in water. Pellets were oven-dried at 60 °C for 24 h, conditioned at 4 °C and 37% relative humidity, and then immersed in water. Pellet mass was recorded at 30-min intervals until structural failure, according to the method of Cheng et al. (2018) (Cheng et al., 2018).

Pellet Toughness

This test was conducted using a pneumatic press machine, known as a Biological Material Test (B.M.T) machine, as shown in Figure 4. The device was designed and built by Kian Mehr and Hassan Baeigi. The load cell used in the test is manufactured by Bongshin (South Korea), while the data logger is from Smart Monitoring Technology Development Company (Iran). The machine's screws are made in Taiwan, with a pitch of 0.5 mm. The pellet was placed radially between the two jaws of the machine (Figure 5) and then loaded at a speed of 25 mm per minute to determine the compressive strength. The machine displays force and time graphs through the manufacturer's software. This machine and its setup are widely referenced in several publications, and the tests were conducted at the Bio-Materials Laboratory at the University of Tehran.

Figure 4. Biological Material Test (B.M.T) machine (Instron): 1) Ball screw for moving the load cell at a specified speed, 2) Load cell, and 3) Inverter

Pellet Scanning electron microscopy

The pellets were analyzed using Scanning Electron Microscopy (SEM) to determine the bonding mechanism of the ground solid waste particles. First, a thin layer of gold coating was applied using a DSR1 sputter coater to achieve optimal conductivity. Then, images were captured using the HITACHI S21160 SEM machine.

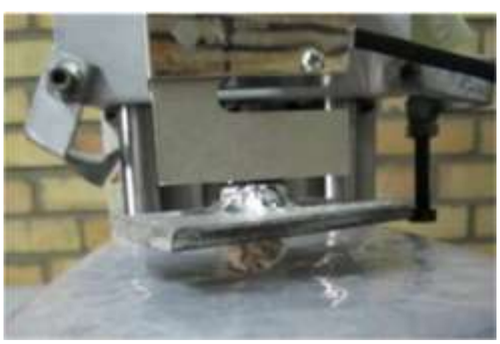

Figure 5. Pellet sample placed radially

Proximate analysis (Moisture, Ash, Volatiles, Fixed Carbon)

For these analyses, an electric furnace capable of reaching 1200°C (Kavoshzema Co., RH-3 model, Iran) was used. The pellets were weighed and placed in a ceramic laboratory furnace. Solid fuel pellets containing plastic materials were subjected to a specially designed test following international standards (Nidhi et al., 2017). To determine the moisture content of the pellets, the samples were dried at 105°C for 1 hour in an oven, and the moisture content was determined according to the standard testing protocol (Montgomery, 1978) from Eq. (1) .

$$W_M\,(\%) = \frac{W_i - W_d}{W_i} \times 100 \quad (1)$$

Where WM is Sample moisture content, Wi is Sample initial weight and Wd is the weight of the sample was reduced after drying.

The ash content test was conducted to evaluate the residue left after burning the pellets. Initially, the samples were heated at 420°C for 1 hour and then burned for 7 hours at 720°C. The percentage of residual ash weight was calculated according to the standard from Eq. (2), the proportion of the remaining weight of ash was determined.

$$W_A\,(\%) = \frac{W_b}{W_i} \times 100 \quad (2)$$

Where WA is Percentage of sample ash, Wi is Sample initial weight and Wb :Ash weight.

The percentage of volatile matter was determined by calculating the weight loss of the pellets after 7 minutes in an oven at 925°C, using the relevant formula from Equations (3) and (4), the proportion of weight loss and moisture content was subtracted.

$$W_L\,(\%) = \frac{W_i - W_h}{W_i} \times 100 \qquad (3)$$

$$W_v\,(\%) = w_L - w_M \qquad (4)$$

Where WL is Weight loss percentage, Wi is Sample initial weight, Wh is Sample weight after removing from the oven, WV is Percentage of volatiles, WM is Sample moisture content and WL is Weight loss percentage.

Finally, the fixed carbon percentage was obtained by subtracting the weight loss percentage and moisture percentage from the total from Eq. (٥).

$$F_C\,(\%) = 100 - (W_M + W_A + W_V) \qquad (5)$$

Where FC is Fixed carbon percentage, WV is Percentage of volatiles, WA is Percentage of sample ash and WM is Sample moisture content.

Calorimetry Test for Heating Value Calculation

The heating value of the prepared pellets with the desired additive was determined using a Cal3K-U solid fuel bomb calorimeter, following the ASTM D2015-96 standard.

Statistical calculations and Data Analysis

The experiments were conducted using a three-factor factorial design, with die temperature at three levels (80, 120, and 160°C), die diameter at two levels (8 and 10 mm), and plastic additive percentage at three levels (0%, 15%, and 25% by weight) based on a completely randomized block design. Duncan's multiple range test at a 0.05 significance level was used to compare the means. Statistical calculations, data analysis, and graph plotting, along with the calculation of mean values, coefficient of variation, minimum and maximum data points, as well as the analysis of variance (ANOVA), were performed using Excel and SPSS software.

RESULTS AND DISCUSSION

In this study, wheat straw and dried grass were initially ground and sieved using a 3 mm sieve and then mixed in equal proportions. The mixture was then combined with polyethylene film, collected as non-recyclable nylon waste, and ground, with plastic additive percentages of 0%, 15%, and 25%. The study examined the effects of process variables, including three temperature levels (80, 120, and 160°C), two die diameters (8 and 10 mm), and three plastic additive levels (0%, 15%, and 25% by weight), on pellet properties such as density, toughness, water retention time, approximate moisture content, volatile matter, ash content, fixed carbon content, heating value, and surface morphology analysis of the pellets.

Density

Based on the evaluation of the density of the produced pellets, the factors of temperature, die diameter, additive material, and the interactions between temperature-die diameter and temperature-die diameter-additive were significant at the 1% level, meaning a 99% probability of significance. However, the interactions between temperature-additive and die diameter-additive were not significant with respect to the density factor completely randomized completely randomized block design. Among these factors, temperature had the most significant effect ($p < 0.01$), while the additive had a less significant effect ($p > 0.05$). The results of mean density comparisons indicated a direct relationship between temperature and density, as increased temperature caused the internal materials of the pellet to flow, releasing the compounds inside. According to Figures 6 and 7, pellets produced at 120°C had higher density compared to those produced at 80°C. Moreover, pellets produced with an 8 mm die diameter had higher density compared to those with a 10 mm die diameter, likely due to the harder bond formation in the 8 mm die (Figure 7). As the temperature increased, the resistance of the particles to the load decreased, resulting in increased pellet density. Furthermore, at a given pressure, increasing the temperature enhanced the compaction and durability of the pellets. Smith et al. obtained similar results. Based on Duncan’s mean comparison method, pellets produced at 120°C and with an 8 mm die diameter had the highest density. Pellets produced at 80°C and with an 8 mm die diameter, as well as those produced at 120°C and with a 10 mm die diameter, had similar density levels. The lowest density was associated with pellets produced at 80°C and with a 10 mm die diameter.

In this study, it was found that plastic begins to soften at temperatures between 103°C and 105°C, and after the pellet cools down, it hardens again, forming suitable pellets. In agricultural residues, lignin in straw and chaff is released between 50°C and 100°C, which acts as a binder for the materials. Additionally, because the pellets were completely dry, with less than 3% moisture content, the disintegration of the pellets was reduced. A smaller die diameter allowed more heat penetration into the material, bonding the core of the pellet more effectively and leading to stronger adhesion between the particles (Gug et al., 2015). As the distance between the particles decreased, intermolecular forces increased, raising the pellet density. It can also be said that the solid bridges formed, making the pellets more cohesive. This behavior can be explained by the fibrous structure of the particles, as demonstrated by the large role of mechanical obstruction in solid-solid interaction, which facilitated pellet formation (Kaliyan & Morey, 2010).

The addition of plastic waste, the additive in this study, may have reduced the distance between fibers, increasing surface contact, and thereby enhancing pellet formation through the growth of short-range forces between particles. This is because van der Waals forces are proportional to particle diameter and inversely exponential to the distance between them (Kaliyan & Morey, 2006). LLDPE, as a binder, has high viscosity and can be absorbed onto the surface of solid particles, forming strong chemical bonds resembling solid bridges. The adhesive forces between the binder and solid particles, as well as within the binder itself, can hold small particles together tightly. Additionally, increasing the temperature causes gelatinization and flow of the internal materials and additives, filling the voids and migrating to the surface of the pellet after softening, forming bridges and binding the materials together to create hard pellets (Forero-Nuñez et al., 2015). When the binder cools and hardens, a solid bridge is formed, connecting the particles.

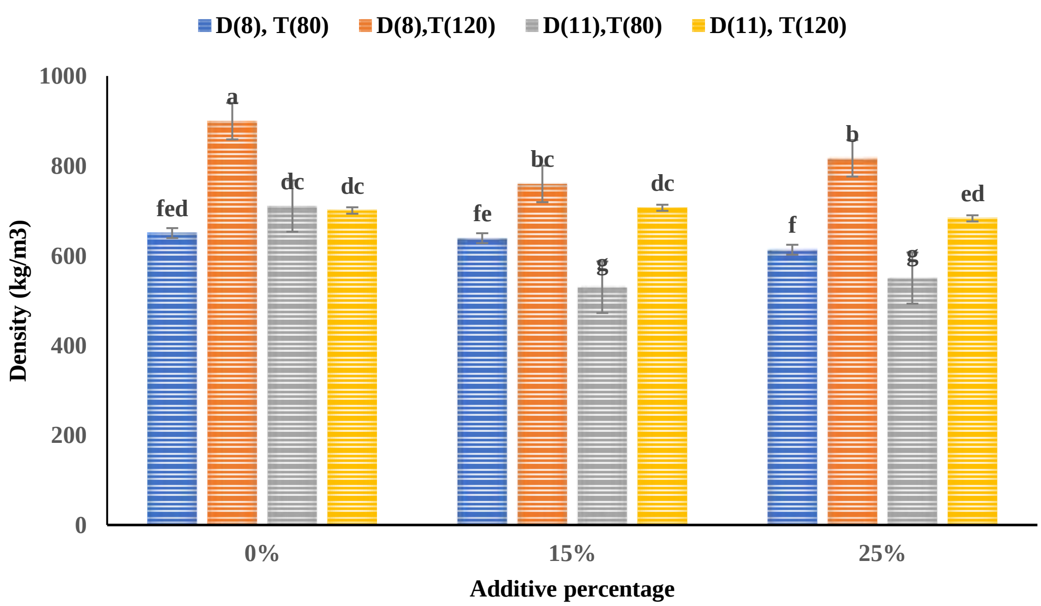

Figure 6. Interaction figure of die diameter, temperature, and additive on pellet density

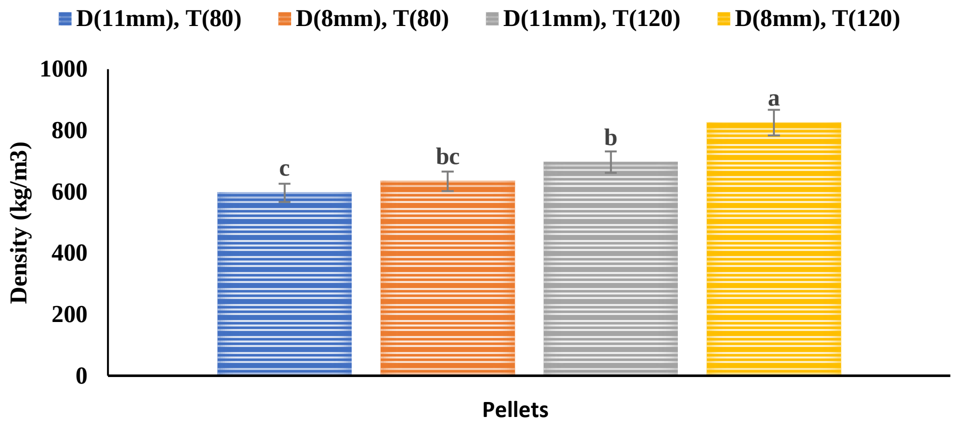

Fig.7. Interaction of die diameter and temperature on pellet density

Toughness

Toughness is the ability of a material to absorb energy and deform plastically before fracturing. Unlike strength, which measures a material's resistance to deformation, and ductility, which refers to the extent of plastic deformation before rupture, toughness accounts for both the material's energy absorption and its resistance to fracture under stress. The analysis of variance for pellet toughness data revealed that all factors were significant at the 1% level, meaning a 99% probability of significance. Among these, the interaction between temperature and die diameter showed the highest significance, while the interaction between die diameter and additive showed the lowest significance. According to Figure 8, as temperature and additive levels increased, pellet toughness also increased. Pellets produced at 120°C were harder, indicating an optimal temperature for bonding the materials. At 160 °C, the toughness of pellets containing 25% additive increased by approximately 216% compared to pellets without additive produced under the same die diameter and temperature conditions.

It was also observed that in pellets with no or low levels of additives, increasing the temperature above 160°C led to a decrease in toughness, making the pellets more brittle. This is because lignin in the biomass softens at around 100°C, and after cooling, it rehardens, increasing the strength of the pellets. However, higher temperatures, such as above 120°C, resulted in more brittle pellets and lower quality. Similar results were observed by Gilbert et al. (Gilbert et al., 2009). In contrast, for pellets with higher plastic content, increasing the temperature also increased toughness. It is speculated that in pellets without additives, increasing the temperature causes complete evaporation of internal moisture, reducing the hydrogen bonds between particles and making the pellets brittle. For pellets with a higher plastic content, the heat fully melted the plastic additive, and as it cooled, the pellets became stronger. Additionally, higher production temperatures can effectively extract lignin from the cells, allowing the pellet particles to bond more strongly (Kaliyan & Morey, 2009; Ramezanzade & Ghazanfari Moghaddam, 2018). The compression of different materials using natural binders or particle bonding mechanisms involves attractive forces between solid particles, interfacial forces, capillary pressure forces, adhesive forces, and cohesive forces, all of which contribute to mechanical bonding (Kong et al., 2012; Liu et al., 2013).

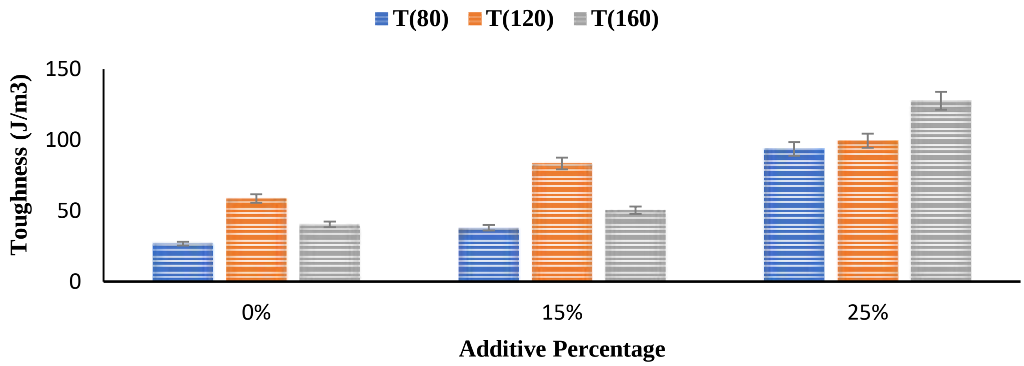

Figure 8. Interaction of temperature and additive on the toughness of fuel pellets

Based on the graph (Figure 9), the interaction effect of die diameter*additive shows that die diameter has a direct impact on the increase in toughness, and this trend continues with the addition of more additives. This is attributed to better compression in the smaller die. In the 8 mm die, there was a 120% increase in pellet toughness as the additive content increased up to 25%.

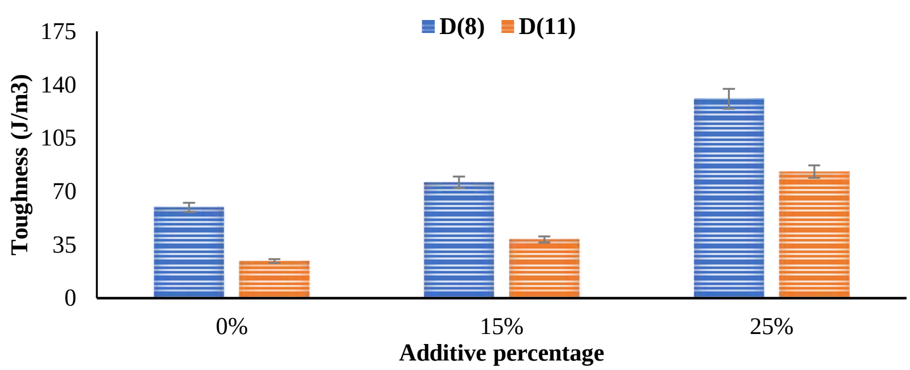

Figure. 9. Interaction of die and additive on the toughness of fuel pellets

Residence Time in water

The factors of die diameter and additive material were significant at the 1% level, meaning a 99% probability of significance for water retention time. According to Figure 10, increasing the additive level up to 25% resulted in a decrease in water absorption by the pellets, which was more pronounced (approximately 60%) in the 8 mm die. The pellets used in the study were compressed at a temperature of 120°C.

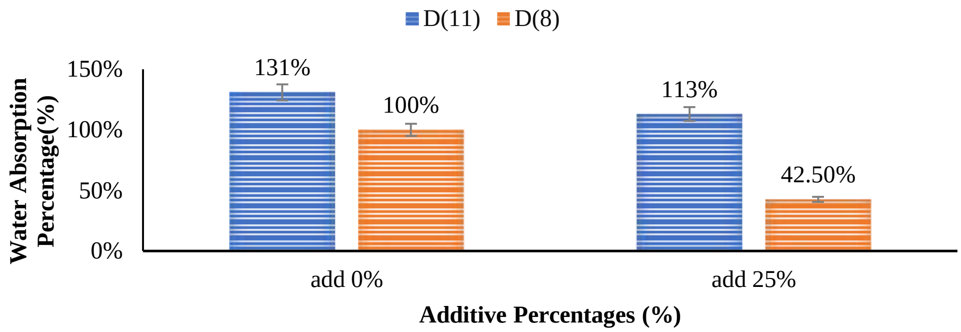

Figure 10. Water absorption percentage of pellets at different die diameters and additive percentages

Figure 11 shows that reducing the die diameter and increasing the additive percentage enhanced the resistance to water disintegration. This is due to the proper bonding of materials in the 8 mm die at 120°C, which reduces the distance between particles, filling the space between them. As a result, plastic and lignin migrate to the pellet surface, creating a hydrophobic coating that prevents water penetration. The shiny appearance of the pellets is due to the lignin coating on their outer surface. Since lignin is naturally hydrophobic, this coating can protect the pellets against water. The slow absorption rate may be attributed to the presence of wax inside the pellet, which migrates to the surface, thus resisting moisture. The higher moisture content of hydrophilic hemicellulose and the lower content of hydrophobic lignin in the pellet composition have been noted (Jiang et al., 2016; Stelte et al., 2011). During compression, the proteins and starch in the raw materials shift into the gaps and cavities between particles, forming a closely-knit structure that prevents water ingress during the first five hours. This knot-like structure was confirmed by SEM analysis (Cao et al., 2015).

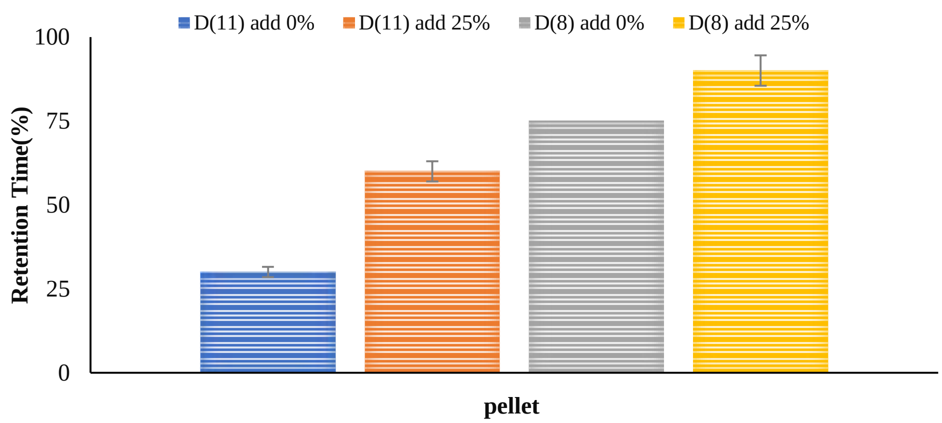

Figure 11. Water absorption percentage of pellets at different die diameters and additive percentages

Calorific Value

Due to the high cost of bomb calorimetry, heating value measurements were limited to a targeted subset of pellets selected to represent the experimental additive levels under a fixed production condition. Accordingly, three pellet samples produced at a die temperature of 120 °C and a die diameter of 8 mm, containing 0, 15 and 25% LLDPE, were tested for heating value determination. As shown in Figure 12, the heating value of pellets made from raw materials without additives was 16.41023 MJ/kg. It was also observed that the tested additive increased the HHV, reaching 21.4874 MJ/kg when the additive percentage was increased to 25%, which represented a 30% increase compared to pellets without additives. Increased plastic content at 80°C significantly improved pellet durability, consistent with previous findings, where the addition of plastic binders enhanced pellet mechanical strength. As reported by Rezaei et al. (2020), plastics possess a high heating value of 46.5 MJ/kg, significantly higher than that of paper at 15 MJ/kg, which supports the incorporation of LLDPE into biomass pellets as a means to enhance their calorific value (Rezaei, Yazdan Panah, et al., 2020). The presence of high-density polymers with long carbon chains contributes to the increase in heating value (Rezaei, et al., 2020).

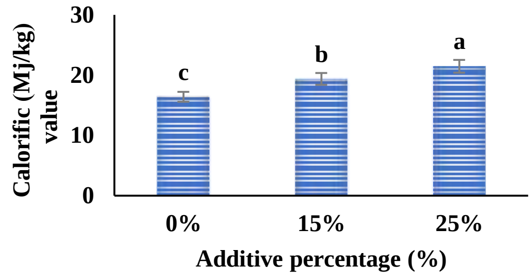

Figure 12. Heating value for different additive percentages in fuel pellets

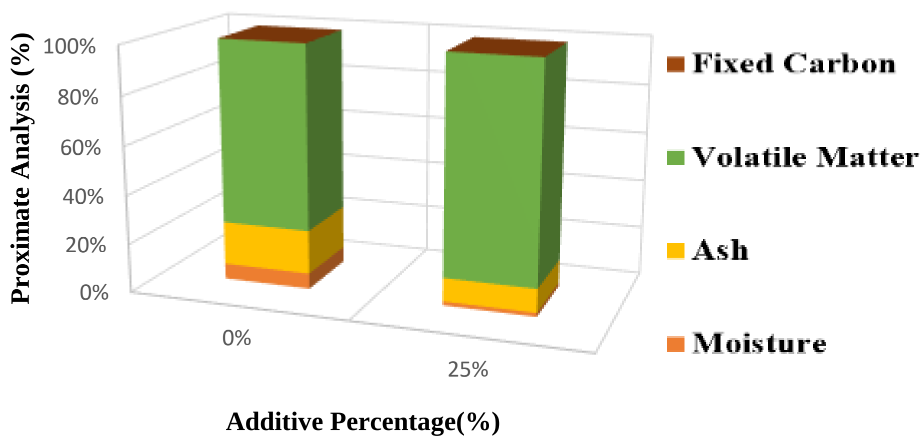

Figure 13. Results of the proximate analysis test

Proximate analysis

An approximate combustion behavior test was conducted for both the produced pellets and the raw powdered materials. This test provided four data points: moisture content, ash content, volatile matter, and fixed carbon, as shown in Figure 13. The results indicated that compaction of the materials led to changes in the approximate percentages. This is likely due to the fact that after compaction, the materials absorbed moisture from the air again, as the spring-back effect of the plastic caused voids to form between the particles.

Table. 1 Higher Heating Value (HHV) of fuel pellets at different LLDPE additive levels

LLDPE additive (wt%)	Heating value ($MJ·kg^{-1}$, HHV)
0	16.41
15	19.38
25	21.49

Table 1. Higher Heating Value (HHV) of fuel pellets produced at 120 °C and 20 s residence time for different LLDPE additive contents. Values indicate an increasing HHV with increasing plastic content.

Table. 2 Proximate analysis of fuel pellets with and without LLDPE additive

LLDPE additive (wt%)	Moisture (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)
0	6.41	17.90	75.64	0.05
25	1.61	9.67	88.71	0.01

Table 2. Proximate analysis of fuel pellets without additive (0%) and with 25 wt% LLDPE. Results show decreased ash and fixed carbon contents and increased volatile matter with increasing LLDPE addition.

Ash content

According to in Figure 13, the ash content of the produced pellets decreased by approximately 46% with the addition of up to 25% LLDPE and LDPE. As the ash content increases, the heating value decreases, a finding that has been confirmed by other researchers (Gillespie et al., 2013). The high potential of LLDPE and plastic materials for reducing ash content is a significant finding. LLDPE, which constitutes a major part of rejected waste, contributes to a reduction in fly ash, with most of the ash settling. The results obtained from the proximate analysis are highly consistent with the materials in the pellets. Given the high content of plastic and polyester in the waste materials, this value is accurate and reliable. Similar results were observed in a study by Nidhi et al. on municipal waste, where values of 0.3%, 0.4%, 99.2%, and 0.12% were obtained for moisture, ash, volatile matter, and fixed carbon, respectively, for LDPE. It was noted that the presence of plastic in the raw materials led to a reduction in ash content and an increase in volatile matter. Overall, PS and LDPE have very high volatile matter in the range of 99.2-99.3%, while their moisture, fixed carbon, and ash content are very low (Nidhi et al., 2017).

Volatile matter

According to Figure 13, the percentage of volatile matter in the pellets increased by 17% in pellets with 25% additive compared to those without additives. Biomass typically contains a large amount of volatile matter, which has a positive effect on combustion stability. It has been noted that the lignin content in biomass has a stronger influence on the heating value compared to other biomass components. In general, the heating value is directly proportional to the fixed carbon and volatile matter content and inversely proportional to the ash content. A high volatile matter content makes biomass a highly reactive fuel with a faster combustion rate during the degradation phase compared to coal (Jamradloedluk & Lertsatitthanakorn, 2017).

Fixed carbon

According to the chart in Figure 13, the fixed carbon content in samples with 25% additive decreased by 80% compared to pellets without additives. Previous studies have suggested that an increase in fixed carbon content leads to higher energy output compared to volatile matter (Du et al., 2014). Additionally, Poddar et al. reported that fixed carbon can burn more steadily and for a longer duration, while volatile matter results in a higher and faster thermal reaction (Poddar et al., 2014).

Interpretation of SEM Scans of Pellets

Based on the SEM images with a resolution of 1 mm, it was observed that pellets produced with the LLDPE additive exhibited greater adhesion, with more solid bridges and locked points visible. In contrast, the images of pellets without additives showed that the fibers were merely layered on top of each other, with insufficient bonding between the particles, and the voids and pores were clearly visible (Figure 14).

No Add **Polyethylene**

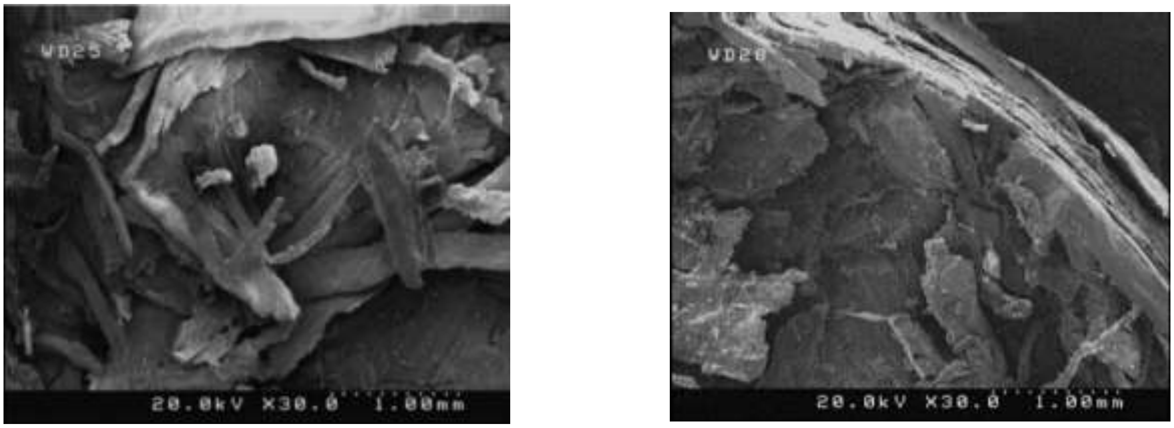

Figure. 14. SEM images of pellet surface morphology at 1 µm scale

CONCLUSIONS

Overall, die temperature was the dominant factor governing pellet quality, while die diameter and LLDPE addition contributed to improved consolidation and performance. Increasing temperature generally enhanced pellet densification and mechanical integrity, and LLDPE addition improved water resistance and increased the heating value due to its polymeric nature. The optimal conditions identified in this study can be used as practical guidance for producing higher-quality biomass-based fuel pellets from agricultural residues and plastic waste.

Proximate analysis confirmed that incorporating LLDPE shifted the pellet composition toward higher volatile matter and lower ash, consistent with the intrinsic characteristics of polyolefins. This compositional shift explains the observed improvement in calorific performance. In parallel, higher processing severity increased the energy demand of pelletization, indicating a trade-off that should be considered when selecting operating conditions for scale-up.

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